Matching a Blumlein Modulator to a Non-Linear Load*

S. Schneider**
Little Silver, NJ 07739

Jim Ferrick
MERADCOM
Fort Belvoir, VA 22060

John L. Carter
US Army Electronics Technology & Devices Laboratory, ERADCOM
Fort Monmouth, NJ 07703

George Dezenberg
MICOM
Redstone Arsenal, AL 35898

Summary

The system studied consisted of a Blumlein modulator driving a sharpening spark gap in series with a carbon felt cathode electron gun. The spark gap is preset to fire at the E-gun operating voltage. A computer simulation of the system was made and was consistent with the system behavior. In order to eliminate large voltage excursions on the E-gun and to achieve a flat top it was necessary to place a capacitor across the spark gap/E-gun combination to provide an initial low impedance load and damp the oscillations. In the 10 microsecond case, in addition to the damping capacitor, it was necessary to taper a few sections of each line of the Blumlein network to compensate for the larger impedance change in the E-gun.

Modulator

Description:

The system[1] consists of a Blumlein modulator to drive a spark gap in series with a carbon felt cathode electron beam gun. The nominal characteristics of the modulator are 34 ohms impedence, a pulse width of 5.5 microseconds, and stored energy of 10,000 joules at 250 kV. The results discussed are at 150 kV. A schematic diagram of the circuit is shown in Figure 1. The circuit works in the following manner. The thyratron short-circuits the front end of the network on the left. This is equivalent to reversing the potential of this network, thus putting it in series with the network on the right. If the gun has an impedance equal to the series rearrangement of the networks, a voltage equal to the original dc charging voltage appears across the gun. The reversal process results in a fixed time delay equal to one-half the pulse width between the firing of the switch and the application of voltage to the gun. A sharpening spark-gap at the input to the e-gun firing at a potential over 160 kV results in about a 100 ns risetime of the voltage applied to the e-gun. In the initial set of conditions discussed the damping capacitor and triggered crowbar gap are not used.

*Partial support by US Army Missile Command, Redstone Arsenal, AL 35898
**Scientific Services Agreement with Battele Columbus Laboratories, Columbus, OH 43201

Voltage and Current Measurements:

The only output voltage monitoring point in the circuit is the voltage across the charging resistor, which is in parallel with the spark-gap e-gun combination. A typical plot of the voltage waveform taken with a Nicolet Explorer III Digital Oscilloscope is shown in Figure 2. The voltage applied directly to the e-gun after the spark-gap fires has to be obtained from a computer simulation.

A current transformer is used to monitor the current through the ground-leg of the e-gun. Unfortunately for safety reasons more than one ground point has been used in the system design. As a result parallel paths for current exist. The current waveforms in Figure 2, show the problem in measuring the e-gun current. Part of the current passing thru the Blumlein switch appears superimposed on the e-gun current. Since the Blumlein switch current appears one-half pulse length before the output voltage is applied to the e-gun, a reversed current appears on the current monitor and superimposes on the e-gun current for one-half of the period of current flow thru the e-gun. This complicates the interpretation of the system behavior. The first 3 μs of the e-gun current from time 0 has been redrawn (dashed line) on Figure 2, adjusted for the reverse current flow from the Blumlein switch.

E-Gun Impedance

The data was analyzed to determine the constant for the time varying impedence, Z(t), of the e-gun in the following Child's Law relationship:

$$Z\ (t) = (d-\overline{v}\ t)^2/kV^{1/2}$$

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1983**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Matching A Blumlein Modulator To A Non-Linear Load**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **MERADCOM Fort Belvoir, VA 22060**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

where k = constant,
d = anode-cathode spacing (15cm),
$\bar{v}$ = closure velocity,
t = time,
and V = applied voltage.

The constants, which give the best fit are:

$k = 4.274 \times 10^{-3}$,
and $v = 0.855$ cm/μs.

Table I lists the calculated values versus the measured values for the gun impedance at specific intervals.

time (μs)	Z meas (Ω)	Z calc (Ω)
1	111	110
2	94	94
3	83.5	83.5
4	81	73
4.5	72	71.5
5	81	79

Table I. Gun Impedance-Measured vs Calculated.

Computer Simulation

The simulation was performed with the Super-Sceptre electrical circuit transient analysis program running on a Cyber 170 central facility computer. The SCEPTRE circuit analysis program determines transient and steady-state responses of large networks from a simple description of circuit topology and component values. The SCEPTRE formulation employs a "state variable" concept and solves the time-dependent set of first order differential equations using numerical integration techniques. The circuits investigated were all comprised of resistive, inductive, or capacitive elements, with switches being approximated as time-dependent resistances. For the circuits described herein, the program generally required less than 120k words (60-bit) of memory, and solutions were usually obtained in 3-5 minutes of CPU time. Reducing component count generally results in faster execution, but avoiding time constants in the circuit subsections which are small compared to the simula tion time is far more important in obtaining computation-efficient solutions. The program was run under the same operating conditions to determine whether the model was correct and would duplicate the measurements. In addition,it provided information on the actual waveform that appears across the e-gun. The following were computed as a function of time:

VBO - Blumlein voltage output across RL3,
IEG - e-gun current,
and VEG - e-gun voltage.

These curves are shown on Figure 3. On Figure 3a, VBO vs time, the actual measurements are plotted on the computer printout for comparison. Examination shows a good correlation between the actual measurements and the computer printout. Figure 3b, IEG vs time, has the corrected current measurement plotted on the computer printout. A good correlation is shown between the corrected current and the computer printout. The actual voltage on the gun, VEG, is shown on Figure 3c.

4 μs Network Modification

The purpose of any proposed modification of the 4 us case was to provide a relatively constant voltage across the gun during the pulse. An important consideration was to provide a modification that was simple to implement and used available capacitors and inductors.

An examination of the e-gun voltage pulse, VEG, shown on Figure 3c shows a large damped oscillation superimposed on the voltage waveform. The series spark-gap fired at 3.45 μs, which we will refer to as time zero. All future times are stated from this reference. At 0.48 μs, VEG reaches a peak of 267 kV and at 0.93 μs drops to 184 kV. It then rises at 1.59 μs to a peak of 220 kV and drops to 190 kV at 2.06 μs. This is followed by two smaller peaks during the remainder of the pulse. Consideration was given to damping the oscillation by adding capacitance to ground at the spark-gap terminal of the coaxial cable. The effect is that the modulator sees initially a low impedance load rather than the initial high impedance load of the e-gun, thus eliminating an initial voltage overshoot that can exceed 25% across the e-gun. The capacitor also tends to act as a voltage clamp. Since the e-gun has an effective impedance of approximately 90 ohms, at a network voltage of 150 kV a peak voltage of 200 kV should appear across the e-gun during the pulse if circuit and switch losses do not exceed 10%. To achieve fast voltage risetime across the e-gun, it is desirable to set the sharpening spark-gap at the e-gun operating voltage.

Three cases were examined. The first two cases were with a 0.03 μf and a 0.06 μf capacitor and the original spark-gap voltage breakdown setting of 164 kV. With the 0.03 μf capacitor, the e-gun voltage is relatively flat for 4 μs with a small oscillation superimposed, particularly at the beginning of the pulse. With a 0.06 μf capacitor, the e-gun voltage is slightly rounded with the oscillations effectively damped. The third case examined was with the 0.03 μf capacitor with the spark-gap breakdown voltage set for 196 kV. The voltage risetime was improved. Table II compares the results.

Case	1	2	3
Damping Cap (μf)	0.03	0.03	0.06
Spark Gap V_b (kV)	164	196	164
Risetime (ns) to 200 kV	23	18	24
E-Gun Volt (kV)-average	197	200	196
Pulse Width (us) for+10kV,-10kV	3.97	3.82	3.89
Pulse Width (us) for+10kV,-20kV	4.25	4.24	4.27

Table II. E-gun voltage waveform as a function of damping capacitance and spark gap breakdown voltage.

On the basis of these results, it was decided that the simplest modification for the 4 µs case would be to place two spare network section capacitors from the spark-gap input terminal to ground and to set the spark-gap voltage breakdown for at least 190 kV. Figure 4 shows the results obtained. The load resistance drops in the 4 µs of operation from 126 Ω to 73 Ω. To complete the simulation a triggered spark-gap with a 1 ohm load was added across the e-gun to crowbar the e-gun 4 µs after the sharpening gap fires. The voltage across the e-gun drops to zero in 270 ns. Thereafter a small oscillation occurs and rapidly decays. The maximum inverse voltage that appears on the cathode is 13% of the peak operating voltage.

The process of modifying the circuit to reduce superimposed oscillations and to make the voltage across the e-gun constant is essentially matching the Blumlein constant impedance networks to, effectively, a constant impedance load with high capacitance. The net effect is that the Blumlein circuit output voltage rises slowly and almost linearly to 200 kV and remains relatively constant throughout the 4 µs that the e-gun is being pulsed. A comparison of Figures 3a and 4a graphically demonstrates the effect of the damping capacitor.

10 us Case

A similar study was performed for a 10 us pulse width. Since the diode spacing is variable it was decided to double the initial impedance of the carbon felt cathode e-gun by changing the diode spacing from 15 cm to 21.2 cm. The pulse length of each line was doubled by increasing the inductance of each section by a factor of 4. Since sufficient network capacitors and mounting hardware are available, three sections were added to each line to achieve the 10 µs pulse width. All computer runs were made using 13 sections for each network. An initial computer run was made without a damping capacitor or crowbar. The results were similar to the initial results obtained in the 4 µs case; the major difference was a change in time scale of a factor of 2.

Based on the results of this computer run it was decided to use the same approach as in the 4 µs case. A damping capacitor of 0.03 µf was added across the input terminal of the sharpening spark-gap and ground. The large oscillations were effectively damped, but the first and last microseconds of the pulse were about 10% low. To compensate for this drop in voltage it proved necessary to reduce the impedance of the first two sections and last two sections of each network to 24 by changing the values of the inductors. This reduced the effective operating pulse length to about 9 µs. Figure 5 shows the results. A crowbar was added to the circuit and fired 10 µs after the ignition of the sharpening spark-gap. Except for some oscillations at the beginning of the pulse, the top is essentially flat at 190 kV for 9 us. During this time the impedance of the gun dropped from 260 Ω to 105 Ω. In order to achieve the full 10 µs flat top, it appears only necessary to increase the initial impedance of the gun and the network sections by another 10%.

Conclusion:

The problem studied was how to match a Blumlein modulator with a non-linear load to achieve a flat top pulse with fast rise and fall time. The specific load used in the study was a carbon felt cathode. Fast rise and fall times are achieved by placing respectively a sharpening spark-gap in series with the e-gun and a crowbar consisting of a triggered spark-gap with a load across the e-gun and the flat top pulse is achieved by placing a damping capacitor across the input of the sharpening gap to ground. The damping capacitor presents an initially low impedance to the Blumlein modulator and prevents the voltage overshoot when the gap fires. The capacitor effectively stores the energy that would appear in the overshoot damping the oscillation, and also tends to clamp the e-gun voltage and compensate for the changing impedance of the load.

1. G. Dezenberg, S. Schneider, and W. Wright, "Modulator-Repetitively Pulsed Field Emission Electron Beam Gun Interface", Proceedings of IEEE International Pulsed Power Conference, November 1976.

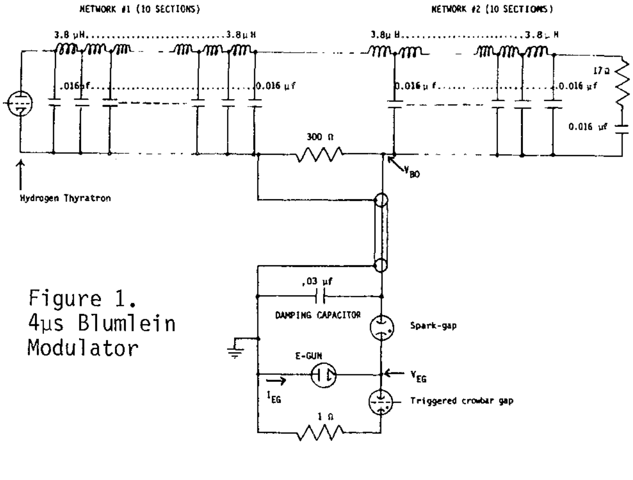

Figure 1.
4µs Blumlein Modulator

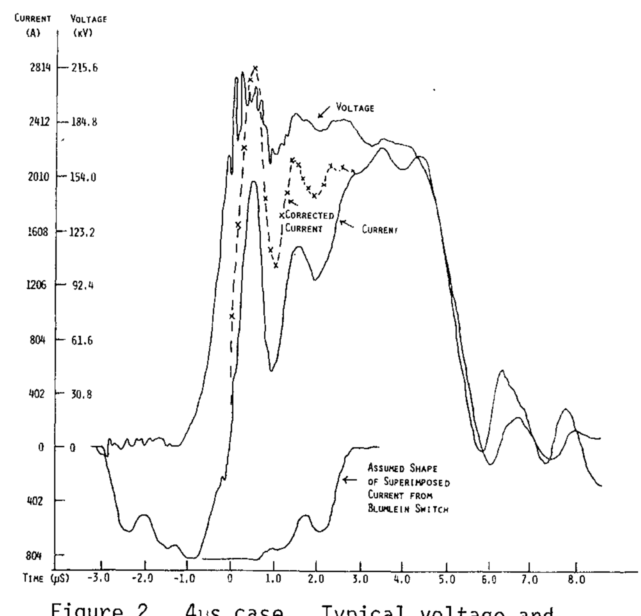

Figure 2. 4µs case. Typical voltage and current measurements at a charging voltage of 150 kV (solid lines). Dashed line is corrected current.

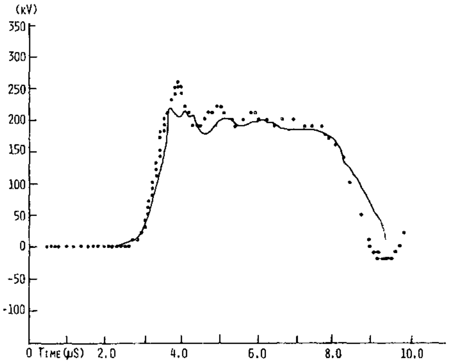

FIGURE 3A
V_{BO} vs TIME WITH ACTUAL VOLTAGE
SUPERIMPOSED (SOLID LINE)
(Inverted)

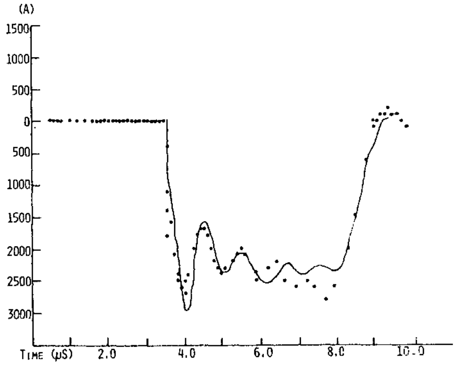

FIGURE 3B
I_{EG} vs TIME WITH CORRECTED CURRENT
SUPERIMPOSED (SOLID LINE)

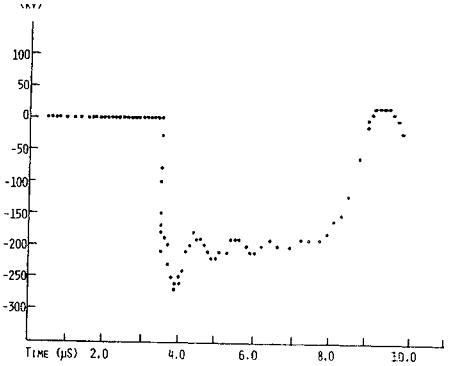

FIGURE 3C
V_{EG} vs TIME

Figure 3. 4μs case. Computer simulation of original circuit with measurement data.

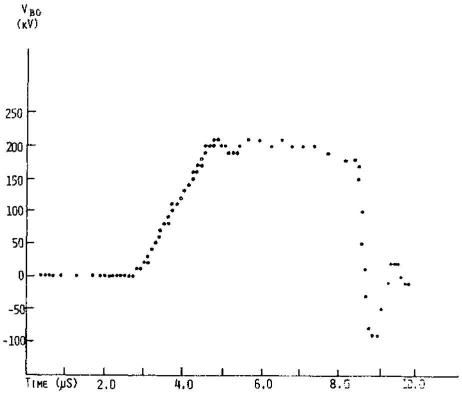

FIGURE 4A
V_{BO} vs TIME
(Inverted)

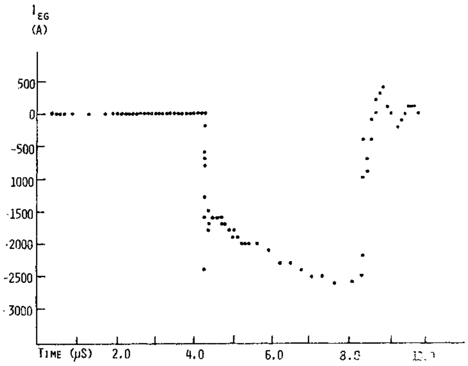

FIGURE 4B
I_{EG} vs TIME

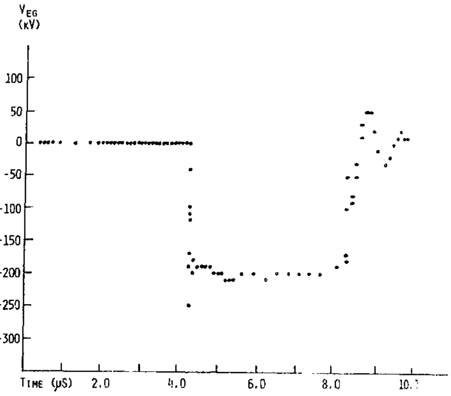

FIGURE 4C
V_{EG} vs TIME

Figure 4. 4μs case. Computer simulation with damping capacitor and crowbar added.

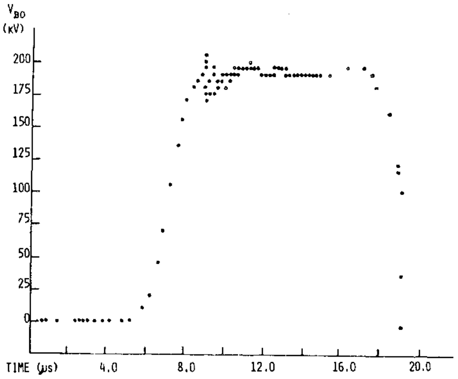

FIGURE 5A
V_{BO} vs TIME
(Inverted)

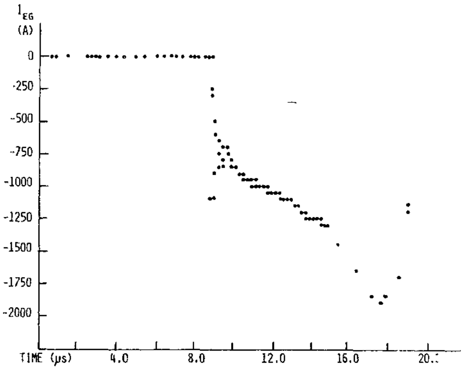

FIGURE 5B
I_{EG} vs TIME

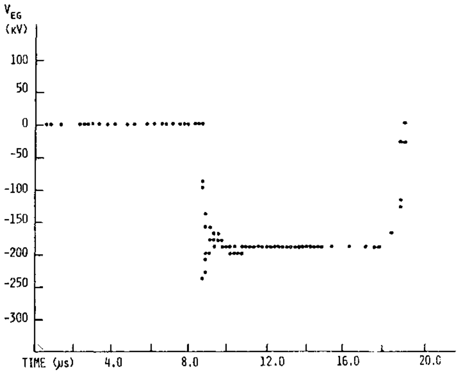

FIGURE 5C
V_{EG} vs TIME

Figure 5. 10μs case. Computer simulation of recommended circuit.